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Redistribution of Mechanical Work at the Knee and Ankle Joints During Fast Running in Minimalist Shoes

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Context: Minimalist shoes have been suggested as a way to alter running biomechanics to improve running performance and reduce injuries. However, to date, researchers have only considered the effect of minimalist shoes at slow running speeds.

Objective: To determine if runners change foot-strike pattern and alter the distribution of mechanical work at the knee and ankle joints when running at a fast speed in minimalist shoes compared with conventional running shoes.

Design: Crossover study.

Setting: Research laboratory.

Patients or Other Participants: Twenty-six trained runners (age = 30.0 ± 7.9 years [age range, 18–40 years], height = 1.79 ± 0.06 m, mass = 75.3 ± 8.2 kg, weekly training distance = 27 ± 15 km) who ran with a habitual rearfoot foot-strike pattern and had no experience running in minimalist shoes.

Intervention(s): Participants completed overground running trials at 18 km/h in minimalist and conventional shoes.

Main Outcome Measure(s): Sagittal-plane kinematics and joint work at the knee and ankle joints were computed using 3-dimensional kinematic and ground reaction force data. Foot-strike pattern was classified as rearfoot, midfoot, or forefoot strike based on strike index and ankle angle at initial contact.

Results: We observed no difference in foot-strike classification between shoes ($\chi^2_1 = 2.29$, $P = .13$). Ankle angle at initial contact was less (2.46° versus 7.43°; $t_{25} = 3.34$, $P = .003$) and strike index was greater (35.97% versus 29.04%; $t_{25} = 2.38$, $P = .03$) when running in minimalist shoes compared with conventional shoes. We observed greater negative (52.87 J versus 42.46 J; $t_{24} = 2.29$, $P = .03$) and positive work (68.91 J versus 59.08 J; $t_{24} = 2.65$, $P = .01$) at the ankle but less negative (59.01 J versus 67.02 J; $t_{24} = 2.25$, $P = .03$) and positive work (40.37 J versus 47.09 J; $t_{24} = 2.11$, $P = .046$) at the knee with minimalist shoes compared with conventional shoes.

Conclusions: Running in minimalist shoes at a fast speed caused a redistribution of work from the knee to the ankle joint. This finding suggests that runners changing from conventional to minimalist shoes for short-distance races could be at an increased risk of ankle and calf injuries but a reduced risk of knee injuries.

Key Words: footwear, footfall, foot strike, kinematics, kinetics

Key Points

- Running in minimalist shoes at 18 km/h caused a shift in foot-strike pattern toward a midfoot foot strike in runners who habitually ran with a rearfoot foot strike in conventional shoes.
- Runners performed more negative and positive work at the ankle joint but less negative and positive work at the knee joint when using minimalist shoes instead of conventional shoes.
- Runners displayed less vertical oscillation of the center of mass when using minimalist shoes instead of conventional shoes.

In recent years, interest in the effects of running barefoot and in minimalist shoes has increased.[1] When running barefoot, more runners make initial ground contact with the forefoot or midfoot, and researchers[2,3] have suggested that this change in foot-strike pattern is a mechanism for reducing injuries and improving performance. Minimalist shoes with reduced cushioning, drop height, and mass have been associated with changes to running gait that are similar to running barefoot.[4–7] Most notably, minimalist shoes can reduce extension moments and negative joint work at the knee, which is one of the most commonly injured joints in running, and improve running economy, which should result in improved race times.[4,7–9] However, much debate remains about the safety of running in minimalist shoes because they also increase plantar-flexion moments and negative work at the ankle joint.[4,7] Researchers[10] have suggested that increased and unaccustomed loading of the triceps surae and Achilles tendon is a mechanism of injury in runners using minimalist shoes.

In a recent survey of 785 runners, Rothschild[11] found that runners had concerns about the safety of using minimalist shoes for long-distance running and were not willing to use minimalist shoes for race distances longer than 5 km. This survey finding has important implications for the current literature on the biomechanics of runners wearing minimalist shoes, which predominantly consists of studies involving slower running speeds (10–14 km/h)[4–7,12,13] that are more typical of longer-distance races than the shorter-distance races that feature minimalist shoes.[11]

Results from a recent 5-km fun-run event showed that the upper 25th percentile of the 472 race finishers had average race speeds of 15 to 20 km/h.[14] These average speeds were faster than the running speeds used in most studies of minimalist shoes,[4–7,12,13] and at speeds greater than 15 km/h, runners are more likely to run with a midfoot or forefoot foot strike, irrespective of the shoes worn.[15] Therefore, minimalist shoes may have reduced effects on running gait at faster speeds. In addition, potential injury in minimalist shoes could be greater when running at faster speeds due to the larger forces involved.[16]

If minimalist shoes do not affect running gait at the fast running speeds that are common to race distances that feature minimalist shoes, runners could be risking injury for no benefit.[10,11] Therefore, the primary purpose of our study was to determine if wearing minimalist shoes instead of conventional shoes caused runners to change foot-strike pattern and joint work at a fast running speed (18 km/h). We hypothesized that more runners would change from a rearfoot foot strike (RF) to a midfoot foot strike (MF) or forefoot foot strike (FF) when running in minimalist shoes compared with conventional shoes. We also expected that running in minimalist shoes would decrease the work at the knee and increase the work at the ankle.

METHODS

Participants

Twenty-six trained male distance runners (age = 30.0 ± 7.9 years, height = 1.79 ± 0.06 m, mass = 75.3 ± 8.2 kg, weekly training distance = 27 ± 15 km) volunteered and completed the study. Sample size was based on studies in which researchers[5,17] compared running biomechanics between minimalist and conventional shoes. We included only participants who were 18 to 40 years old, trained with conventional running shoes, were habitual RF runners (typical of 89% of runners),[18] had a weekly training distance of 15 km or more, and had no experience with running in minimalist shoes. We excluded participants with a musculoskeletal injury sustained less than 3 months before the study. Foot-strike–pattern eligibility was determined from overground running trials during which participants wore their usual shoes, ran at self-selected speeds, and were filmed at 200 Hz using a high-speed digital camera (Basler Pilot, Ahrensburg, Germany) placed at ground level 5 m from a runway and perpendicular to the sagittal plane. Participants performed 5 running trials, and only runners who landed with their heels first in all 5 trials were included. We allowed them to select their running speed for the assessment of foot-strike–pattern eligibility to ensure that we assessed habitual running biomechanics.[19] Running speeds ranged from 11 to 15 km/h. We recruited an additional 10 participants to complete the study protocol in their regular shoes on 2 occasions to determine test-retest reliability for all outcome measures. All participants provided written informed consent, and the study was approved by the Human Research Ethics Committee of the University of South Australia.

Experimental Conditions

We used a crossover design with 1 conventional and 1 minimalist shoe condition. Each participant completed overground running trials in each type of shoe on separate days. The order of conditions was randomized and balanced across participants. The conventional shoe was an Asics Gel Cumulus-14 (mass = 318 g per shoe, heel-stack height = 32 mm, heel drop = 9 mm; Asics Corporation, Kobe, Japan), and the minimalist shoe was an Asics Piranha SP4 racing flat (mass = 125 g per shoe, heel-stack height = 22 mm, heel drop = 5 mm; Asics Corporation). Shoe mass is reported for an average US size 9 (European size 42.5) shoe. The Asics Piranha meets published standards for minimalist shoe classification and scored 72% on the minimalist index for classification of running shoes on a scale from *least minimalist* (0%) to *most minimalist* (100%).[20] In contrast, the Asics Gel Cumulus scored 16% on the minimalist index. Before the biomechanical assessments, participants completed 2 minutes of submaximal running in the respective shoe condition to familiarize themselves with the shoe type. No other shoe familiarization was provided for participants because we were investigating the immediate effects of running in different shoe types.

Experimental Set-Up

Overground running was assessed along a 40-m straight runway. Three-dimensional kinematic data were collected using a 12-camera system (model MX-F20; Vicon Motion Systems Ltd, Oxford, United Kingdom) sampling at 300 Hz. Ground reaction force data were collected using a 900-mm × 600-mm force plate (Kistler Instrument Corp, Amherst, NY) sampling at 1200 Hz. Cameras were positioned around the force plate to achieve a 2-m × 2-m × 8-m capture volume. We monitored the consistency of running speed using photoelectric sensors (SpeedLight V2; Swift Performance Equipment, Queensland, Australia).

Participants completed 5 successful overground running trials at 18 ± 1.8 km/h in each condition. A *successful trial* was defined as one in which the full plantar surface of the foot made contact with the force plate at the prescribed running speed without obvious modification of gait. We did not instruct participants to target the force plate; instead, we adjusted the runway starting point as needed to facilitate a successful trial. The body was represented by a 12-segment rigid-body model, which consisted of the feet, shanks, thighs, pelvis, trunk and head, arms, and forearms with hands. Each body segment was modeled using 6 degrees of freedom. Spherical retroreflective markers, which were used to define the position and orientation in space of each segment, were placed over the first and fifth metatarsal heads, lateral and medial malleoli, lateral and medial femoral epicondyles, greater trochanters, anterior-superior iliac spines, posterior-superior iliac spines, C7 spinous process, acromioclavicular joints, lateral and medial humeral epicondyles, and radial and ulnar styloid processes. A minimum of 3 noncollinear markers were used to track the position and orientation in space of each segment.

Data Processing

Force plate and motion data were synchronized using Nexus software (version 1.8; Vicon Motion Systems Ltd), and data were imported into Visual3D software (version 5; C-Motion Inc, Germantown, MD) for postprocessing. Marker trajectory and ground reaction force data were filtered using a recursive fourth-order, low-pass Butterworth filter with cutoff frequencies of 25 Hz and 50 Hz, respectively. The cutoff frequency for marker trajectories was determined using a residual analysis of tracking markers from each segment.[21] The body segment measures (mass, moments of inertia, and center of mass [COM] position) were determined from anthropometric data reported by Dempster.[22] The whole-body COM was calculated from the weighted sum of each segment's COM. For each trial, 1 complete stance phase was analyzed. Given that no a priori reason existed to expect differences between the right and left sides, analysis was limited to the right lower limb to avoid artificially inflating statistical power by combining data for the right and left limbs.[23]

Analysis was limited to the sagittal plane. Joint angles were computed as Euler angles using the joint coordinate system as recommended by the International Society of Biomechanics.[24,25] Strike index was calculated using the center-of-pressure location at initial contact along the long axis of the foot and expressed as a percentage of total foot length.[26] We classified participants as RF runners if the strike index was less than 33% and the ankle angle at initial contact was greater than 5° of dorsiflexion, MF runners if the strike index was 34% to 66% and the ankle angle at initial contact was between 5° of dorsiflexion and 5° of plantar flexion, and FF runners if the strike index was greater than 66% and the ankle angle at initial contact was greater than 5° of plantar flexion.[19] Joint work was considered the integral of the joint power-time curve. We calculated negative and positive work from the negative (ie, eccentric muscle action) and positive (ie, concentric muscle action) components, respectively, of the power-time curve.

Statistical Analysis

We averaged data for each participant across 5 trials for each shoe condition. Normality of data was checked using Shapiro-Wilk tests. Differences between conditions were examined using paired-samples *t* tests for continuous variables and the McNemar test with Yates correction for categorical foot-strike–pattern data. No corrections were made for multiple comparisons. Standardized mean differences (SMDs) were calculated using the pooled-group standard deviation. Standard error of measurement (SEM) was calculated for each outcome using test-retest data collected from the 10 additional participants who completed the study protocol in their regular shoes on 2 occasions. Differences between shoes that were less than the SEM were not considered to be true differences. The α level was set at .05. All statistical analyses were performed using SPSS software (version 19; IBM Corporation, Armonk, NY).

RESULTS

No runners used an FF when running in either shoe type. Eight runners used an MF in minimalist shoes, and 3 used an MF in conventional shoes ($\chi^2_1 = 2.29$, $P = .13$; Table). Using minimalist shoes increased the strike index (Table).

Runners landed with a more plantar-flexed ankle at initial contact in minimalist shoes, but we observed no difference in peak ankle dorsiflexion or ankle angle at toe-off between shoes (Table). Running in minimalist shoes increased negative and positive work at the ankle joint (Table). Negative work occurred at the ankle joint during the initial approximately 60% of stance when the ankle was moving into greater ankle dorsiflexion, indicating eccentric muscle action of the ankle plantar-flexor muscles (Figure 1). Positive work occurred at the ankle joint during the final approximately 40% of stance when the ankle was moving into greater ankle plantar flexion, indicating concentric muscle action of the ankle plantar-flexor muscles (Figure 1).

Running in minimalist shoes decreased negative and positive work at the knee joint (Table). Negative work occurred at the knee joint during the first approximately 40% of stance when the knee was moving into greater knee flexion, indicating eccentric muscle action of the knee-extensor muscles (Figure 2). Positive work occurred at the knee joint from approximately 40% to approximately 90% of stance when the knee was moving into greater knee extension, indicating concentric muscle action of the knee-extensor muscles (Figure 2).

Mean differences between shoes for all knee kinematic variables were less than the SEM and may not have represented true differences (Table). Similarly, the mean difference in stride length between shoes was less than the SEM. Running in minimalist shoes increased the stride rate but decreased the contact time and vertical displacement of the whole-body COM (COM_{vert}; Table).

DISCUSSION

The purpose of our study was to determine if running biomechanics differed between minimalist and conventional shoes at a fast running speed. We hypothesized that more runners would change from an RF to an MF or FF when running in minimalist shoes compared with conventional shoes. We also expected minimalist shoes to decrease work at the knee and increase work at the ankle. Our hypotheses were partially supported by the results of this study. Using minimalist shoes increased the strike index and decreased the ankle angle at initial contact, which is consistent with runners using an MF. However, we observed no difference in overall foot-strike–pattern classification between shoes. This null finding may have resulted from a type II error because a post hoc power analysis indicated only 50% power for the analysis of categorical foot-strike–pattern data. Consistent with our hypothesis, using minimalist shoes increased work at the ankle and decreased work at the knee.

We are the first to investigate the effects of minimalist shoes on running biomechanics at a speed faster than 16 km/h.[17] In most studies of minimalist shoes, researchers[4–7,12,13] have used slower speeds (<14 km/h) to investigate running biomechanics. Runners predominantly use minimalist shoes for short-distance races (<5 km),[11] and over these shorter distances, running speed is often greater than 14 km/h. Our findings are directly relevant to this practice.

The largest effects of minimalist shoes were observed for strike index (SMD = 0.72) and ankle angle at initial contact (SMD = 0.62). Mean strike index (35.97%) and ankle angle at initial contact (2.46° of dorsiflexion) for runners using minimalist shoes were within the typical range for MF runners.[19] These results are consistent with the findings of

Table. Differences in Spatiotemporal, Kinematic, and Kinetic Variables Between Shoe Types

Variable	Shoe Type, Mean ± SD: Conventional[a]	Minimalist[b]	Mean Difference (95% Confidence Interval)	*t* Value	*P* Value	Standard Error of Measurement[c]	Standardized Mean Difference (95% Confidence Interval)
Stride length, m	3.51 ± 0.20	3.46 ± 0.19[j]	−0.05 (−0.01, −0.09)	2.18	.04	0.05	0.25 (0.02, 0.48)
Stride rate, strides per min	86.18 ± 5.57	87.89 ± 6.50[j]	1.71 (0.73, 2.69)	3.60	.001	1.46	0.28 (0.12, 0.44)
Contact time, s	0.203 ± 0.012	0.196 ± 0.012[j]	−0.007 (−0.003, −0.011)	3.41	.002	0.005	0.58 (0.23, 0.93)
Vertical displacement of the center of mass, mm	69.80 ± 9.46	67.03 ± 10.08[j]	−2.77 (−0.72, −4.83)	2.78	.01	2.52	0.28 (0.07, 0.49)
Strike index, %	29.04 ± 6.03	35.97 ± 13.12[j]	6.93 (0.93, 12.93)	2.38	.03	4.40	0.72 (0.10, 1.34)
Ankle							
Initial contact angle, °[d]	7.43 ± 6.75	2.46 ± 9.29[j]	−4.97 (−1.90, −8.04)	3.34	.003	1.93	0.62 (0.24, 1.00)
Peak dorsiflexion, °[d]	20.98 ± 3.44	21.96 ± 3.38	0.98 (−0.09, 2.04)	1.89	.07	2.39	0.29 (−0.02, 0.60)
Toe-off angle, °[d]	−21.38 ± 3.77	−22.25 ± 3.90	−0.87 (−2.29, 0.55)	1.26	.22	3.01	0.23 (−0.14, 0.60)
Negative work, J[e]	42.46 ± 18.08	52.87 ± 21.73[j]	10.41 (1.03, 19.79)	2.29	.03	6.62	0.52 (0.05, 0.99)
Positive work, J[f]	59.08 ± 15.97	68.91 ± 17.82[j]	9.83 (2.18, 17.47)	2.65	.01	5.25	0.58 (0.13, 1.03)
Knee							
Initial contact angle, °[g]	10.66 ± 4.97	12.61 ± 5.30[j]	1.95 (0.43, 3.47)	2.64	.01	1.98	0.38 (0.08, 0.68)
Peak flexion, °[g]	41.91 ± 3.47	40.40 ± 2.69[j]	−1.51 (−0.45, −2.56)	2.94	.01	2.46	0.49 (0.15, 0.83)
Toe-off angle, °[g]	11.82 ± 4.34	12.54 ± 4.51	0.71 (−0.63, 2.05)	1.09	.29	1.15	0.16 (−0.14, 0.46)
Negative work, J[h]	67.02 ± 19.39	59.01 ± 19.41[j]	−7.93 (−0.65, −15.21)	2.25	.03	5.71	0.41 (0.03, 0.79)
Positive work, J[i]	47.09 ± 17.06	40.37 ± 17.13[j]	−6.72 (−0.13, −13.31)	2.11	.046	5.40	0.40 (0.01, 0.79)

[a] For conventional shoes, 23 runners had rearfoot foot strike, 3 had midfoot foot strike, and 0 had forefoot foot strike.
[b] For minimalist shoes, 18 runners had rearfoot foot strike, 8 had midfoot foot strike, and 0 had forefoot foot strike.
[c] Calculated from test-retest measurements taken from 10 additional participants who completed the study protocol in their own shoes.
[d] Positive angles indicate dorsiflexion.
[e] Negative work indicates eccentric muscle action of the ankle plantar-flexor muscles.
[f] Positive work indicates concentric muscle action of the ankle plantar-flexor muscles.
[g] Positive angles indicate flexion.
[h] Negative work indicates eccentric muscle action of the knee-extensor muscles.
[i] Positive work indicates concentric muscle action of the knee-extensor muscles.
[j] Different from conventional shoe ($P < .05$).

Squadrone and Gallozzi,[6] who reported that minimalist shoes increased the strike index and decreased the ankle angle at initial contact at a slower speed (12 km/h). In contrast, these results are not consistent with the findings of Bonacci et al,[17] who noted no effect of minimalist shoes on ankle angle at initial contact in elite runners. Differences across studies may have resulted from heterogeneity in minimalist footwear and participant training status. Indeed, in a recent study involving 6 different types of minimalist shoes, Squadrone et al[5] observed different effects on the strike index and ankle angle at initial contact across shoes. They suggested that minimalist shoes with a smaller heel-stack height (7–13 mm) were more likely to change running biomechanics than minimalist shoes with a greater stack height (22–26 mm) because the latter provides more protection for the heel and allows a more comfortable RF.[5] However, contrary to this finding, the minimalist shoes in our study had a heel-stack height of 22 mm and still caused runners to alter the strike index and ankle angle. Therefore, the effects of minimalist shoes on foot-strike pattern may not be explained solely by differences in heel-stack height.

Changes to the strike index and ankle angle when using minimalist shoes were accompanied by a redistribution of negative and positive work from the knee to the ankle joint. This finding is consistent with previous research[4,7] in which the authors demonstrated that running in minimalist shoes at slower speeds (<12 km/h) increased negative work and peak power at the ankle but decreased negative work and peak power at the knee compared with running in conventional shoes. Redistributing loading from the knee to the ankle joint might allow greater elastic-energy storage and recovery in the Achilles tendon, which could contribute to greater mechanical efficiency and race performance.[4,27] However, increased negative work at the ankle requires increased eccentric muscle action by the ankle plantar-flexor muscles, which could increase the risk of injury to the Achilles tendon and triceps surae.[28] Runners transitioning to minimalist shoes should make this change slowly to allow time for the triceps surae and Achilles tendon to adapt to the increased eccentric muscle action.

Whereas running in minimalist shoes could increase the injury risk at the ankle joint, the opposite could be true for the knee joint. Goss et al[7] demonstrated that using minimalist shoes reduced negative work at the knee joint when running at a slower speed (10 km/h), and our results suggested that this difference persists at faster running speeds. Reduced work at the knee joint might have resulted from the increased stride rate and strike index that occurred when using minimalist shoes. Researchers[29,30] have demonstrated that running with an increased stride rate or an FF decreases knee-joint contact forces. Therefore, minimalist shoes could be used to reduce the risk of injury at the knee, which is one of the most commonly injured joints in running,[9] by facilitating an MF and increased stride rate. Future prospective studies are needed to investigate the long-term efficacy of using minimalist shoes in this manner.

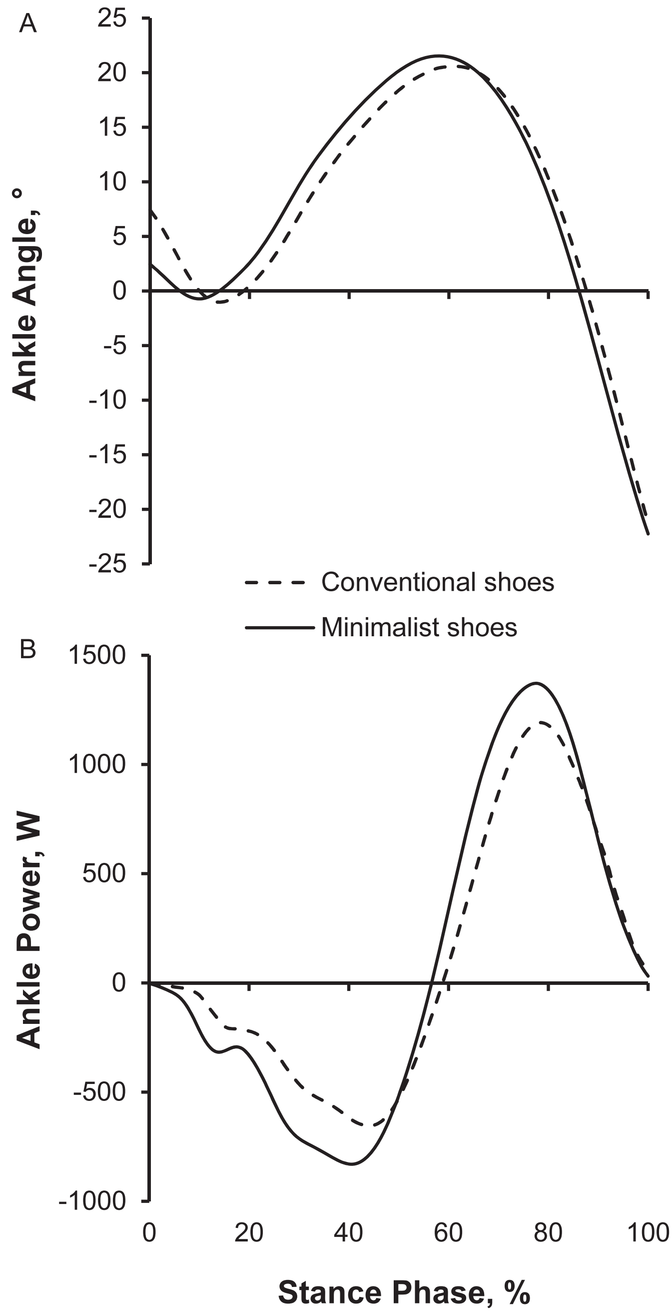

Figure 1. Group mean ankle-joint, A, angle and, B, power during a complete stance phase for minimalist and conventional shoes. Positive joint angles indicate ankle-joint dorsiflexion, and negative joint angles indicate ankle-joint plantar flexion. Positive joint power indicates generation of energy (concentric muscle action of ankle plantar-flexor muscles), and negative joint power indicates absorption of energy (eccentric muscle action of ankle plantar-flexor muscles).

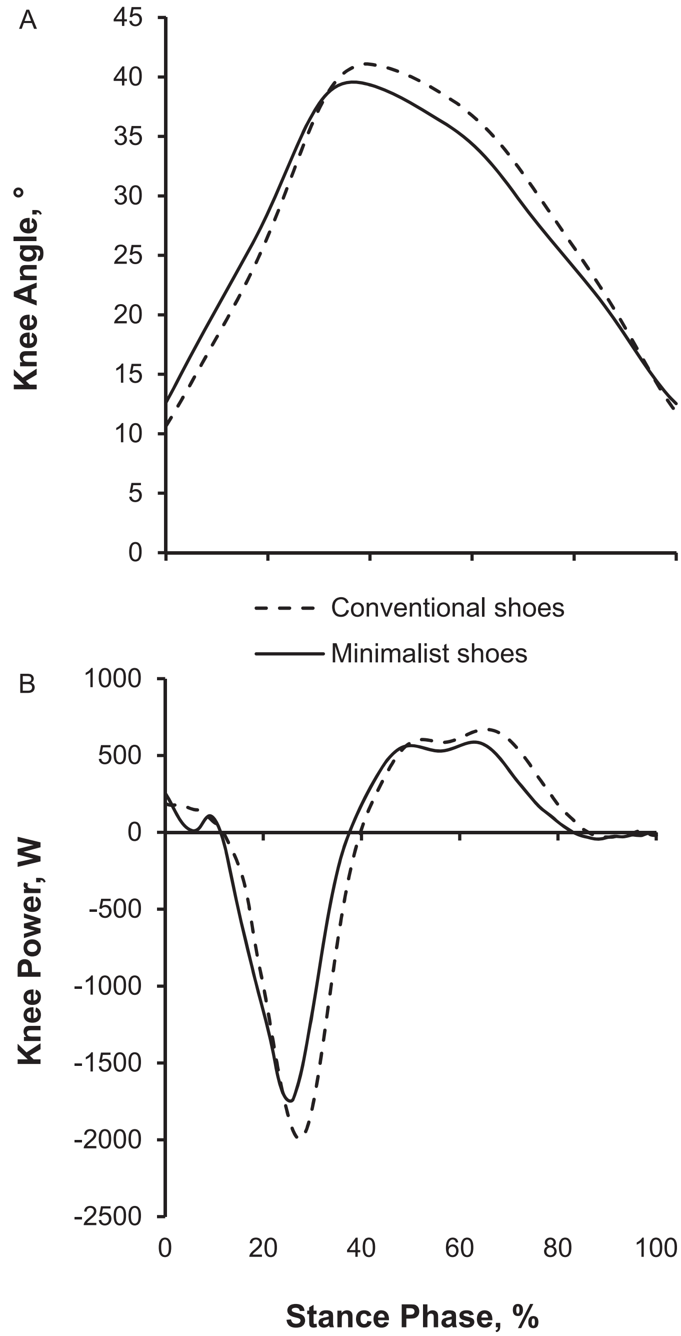

Figure 2. Group mean knee-joint, A, angle and, B, power during a complete stance phase for minimalist and conventional shoes. Positive joint angles indicate knee-joint flexion, and negative joint angles indicate knee-joint extension. Positive joint power indicates generation of energy (concentric muscle action of knee-extensor muscles), and negative joint power indicates absorption of energy (eccentric muscle action of knee-extensor muscles).

Using minimalist shoes was accompanied by small reductions in COM_{vert}. The lower COM_{vert} indicated a more efficient running gait in minimalist shoes because it suggested that runners were required to perform less mechanical work against gravity.[13,27] Thus, a reduced COM_{vert} could explain the improvements in running economy that have been observed in runners using minimalist shoes even when controlling for changes in foot-strike pattern and stride rate.[3] Runners might have achieved a lower COM_{vert} when using minimalist shoes by reducing the range of motion at the knee and ankle.[13] However, differences in peak knee flexion and peak ankle dorsiflexion between shoes were less than the SEM, and it remains unclear how the range of motion at these joints influenced the COM_{vert} in minimalist shoes.

Our study had important limitations that should be considered when interpreting our findings. First, differences between the shoes in our study represent the immediate effects of using minimalist shoes, and it is unclear whether these acute changes would translate to long-term changes in foot-strike pattern and joint work. Second, to model the foot, we used a single segment, which did not account for motion at the rearfoot, midfoot, or forefoot joints. Third, the risk of type I error was increased by comparing shoes across multiple outcomes. Fourth, we investigated only 1 type of minimalist shoe. The shoe mass, heel drop, and stack height of the racing flat used in our study were equivalent to those of several other minimalist shoes (Saucony Kinvara 2 [Wolverine World Wide, Inc, Rockford, MI], Nike Free 3.0 [Nike, Inc, Beaverton, OR], and Newton Running MV2 [Newton Running Company, Boulder, CO]), but the heel drop and stack height were slightly greater than those of some minimalist shoes on the market (Inov8 Bare-X 200 [Inov8, Southborough, MA], New Balance MR00GB [New Balance Athletics, Inc, Boston, MA], and Vibram FiveFingers [Vibram USA, Concord, MA]).[5] Nonetheless, racing flats have been used by runners for many years and can be considered representative of the running footwear used before the introduction of modern conventional running shoes.[11,17] Therefore, racing flats are well suited to investigations of minimalist footwear.

CONCLUSIONS

Running in minimalist shoes caused a shift in foot-strike pattern toward an MF, even at fast running speeds that represent the average running speeds associated with short-distance races. This change requires more work from the ankle plantar-flexor muscles but less work from the knee-extensor muscles. Therefore, runners changing from conventional to minimalist shoes for short-distance races could be increasing their ankle-injury risk but reducing their knee-injury risk. Using minimalist shoes reduced COM_{vert}. This reduction suggests a more efficient running gait and might explain some of the improvements in running economy that occur when using minimalist shoes.

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CONFLICTS OF INTEREST

Dr Thewlis received funding from ASICS Oceania (ASICS Oceania Pty Ltd, Eastern Creek, New South Wales, Australia) to undertake separate research.

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